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The Encyclopedia of Life *vs.* the Brochure of Life: Exploring the relationships between the extinction of species and the inventory of life on Earth

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One of the most crucial questions of twenty-first century systematic biology deals with the determination of the real number of living species currently sharing the Earth with us (Cracraft 2002); answers vary widely, but commonly range between 3 and 100 million (see, for example, Stork 1997 or May 2002 and references therein). However, in terms of completeness and correctness, our current inventory of living species is certainly unsatisfactory (Dubois 2003), as the total number of species described so far is known to correspond to only a very small fraction of the Earth´s biodiversity. Indeed, large numbers of species remain to be discovered, primarily insects, small invertebrates and, above all, microorganisms (Chevalier et al. 1997). On the other hand, this gap of knowledge regarding the magnitude of the Earth´s biodiversity limits our capacity to properly manage the world´s biotic resources and conserve biological diversity in this so-called Century of Extinctions (Dubois 2003): the current biodiversity crisis is wiping out a significant fraction of living species at an alarming rate and, sadly, an unknown number of species is being forever lost before being discovered, described, and named. Likewise, conservation priorities are clearly constrained by our limited knowledge of the total biodiversity (Dubois 2003, Scotland et al. 2003).

Assuming that 1.5–2 million eukaryote species have been collected, studied and named from Linnaeus' work until now (Cracraft 2002, May 2002, Mace et al. 2005), and that the total figure might lie somewhere between 10–20 million, some authors (Wilson 2003b, 2005) consider feasible to discover, describe and name, in a limited time span, all eukaryote species roaming the Earth. To allow the completion of this Encyclopedia of Life, as it has been termed (Wilson 2003b; see also Wilson 2006), it is imperative to overcome the so-called taxonomic impediment (Dubois 2003, Wheeler et al. 2004, de Carvalho et al. 2005, Evenhuis 2007) which is currently obstructing much needed advancement in sound management of known species (Crisci 2006) and discovery of unknown ones (de Carvalho et al. 2007, Evenhuis 2007). In short, the taxonomic impediment results from (i) deep knowledge gaps in our taxonomic system, (ii) the lack of expert taxonomists and curators to handle the enormous, overwhelming task of classifying the unknown biodiversity and (iii) the impact of these two limitations on our ability to conserve, use and share the benefits of biological diversity. Although it is also questionable, for this paper I will assume that we can not enjoy and protect something if we don't know what is out there to enjoy and protect (Evenhuis 2007). On this matter, and based on his own museum experience, Wilson (2004) reckons that if we double the current number of practising taxonomists (at the moment, it is estimated to be *ca.* 6,000–7,000 taxonomists) (Schnack & López 2003, Wilson 2004), and provide each of them with the help of several technical assistants and novel technologies (*e.g.*, genomic maps, web publication, etc.), the global biodiversity survey could be completed within a single human generation, *i.e.* 25 years. Nonetheless, other authors (May 2004) have expressed doubts about the feasibility of this vast project, particularly taking into account the present rate of new species description, *i.e.*, around 10,000 species per year considering the synonymy load (May 2002, 2004, Dubois 2008).

Completing the Encyclopedia of Life in 25 years: numbers don't tally

In order to throw some light on this issue, I modelled the behaviour of the total number of species known at year t (Sk_t) as a linear function of the figure at year t-1, plus the net amount of new species described each year (Nw = 10,000). In order to be cautious, I considered only one value for the total number of species known at year 2000 (Sk_{2000}), *i.e.*, a low estimate

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of 1.5 million. This scenario describes the situation expected if no actions are taken to overcome the abovementioned taxonomic impediment. Furthermore, to simulate those conditions reported by Wilson (2004) as necessary for the completion of the Encyclopedia of Life in just 25 years, I multiplied *Nw* by 2, but also by 3, 5, 10 and 15, to allow for the possibility that an increment in the number of practising taxonomists could result in more than the corresponding multiplication of the rate of species discovery, and also to take into consideration the expected positive effects derived from the help of the technical assistants and novel technologies. Moreover, and following May (2004), I enriched the model by incorporating the effects of the formation and extinction of species: speciation rate (*Spec*) has been reported to be between one species per 10^5 to 10^7 species per year in the best chronicled taxa, with most falling closest to one species per 10^6 species per year (Wilson 2003a); therefore, I used this last value (one per 10^6 species per year) for all my calculations. Current extinction rates (*Ext*) are estimated to be 100 to 1,000 times their pre-human, background levels (Pimm et al. 1995, May 2002, Wilson 2003a); I used the highest value (*Ext* = 1000**Spec*) and, therefore, *Ext* was set to one species per 10^3 species per year (probably, closer to the real value; Wilson 2003a). Then, I modelled the dynamics of biodiversity by applying the exponential model, $TS_t = TS_0 e^{rt}$ (see, for example, Gotelli 2001); in this case, TS_t is the total number of species at time *t*, TS_0 is the total number of species at time 0, and *r* is the difference between *Spec* and *Ext*. I considered three initial values of TS_0, a low (3 million), a medium (10 million) and a high (100 million) estimate.

Given that *Spec* < *Ext*, then biodiversity is declining; nonetheless, the magnitude of the reduction in the total number of species in 25 years appears small, *i.e.*, an average reduction of just 0.25% of the initial biodiversity. Importantly, if no actions are taken to overcome the abovementioned taxonomic impediment, then it appears impossible to complete the Encyclopedia of Life in just 25 years; at worst (if the total number of species at year 2000 is as high as 100 million), only 1.8% of the unknown biodiversity would be identified (Figure 1); at best (if TS_0 = 3 million), around 60% (Figure 1). In addition, if TS_0 = 3 million, then, in order to discover all the remaining species in just 25 years, efforts to describe new species should be multiplied by a factor of 10 (or more; Figure 1). However, should the magnitude of biodiversity be close to 10 million, a value considered as more plausible by both Wilson (2003b) and other authors (May 2002, Mace et al. 2005), or higher, as 100 million, then the completion of the Encyclopedia of Life would take much longer (Figure 1), unless *Nw* is increased by a factor much higher than 15. But, how much?

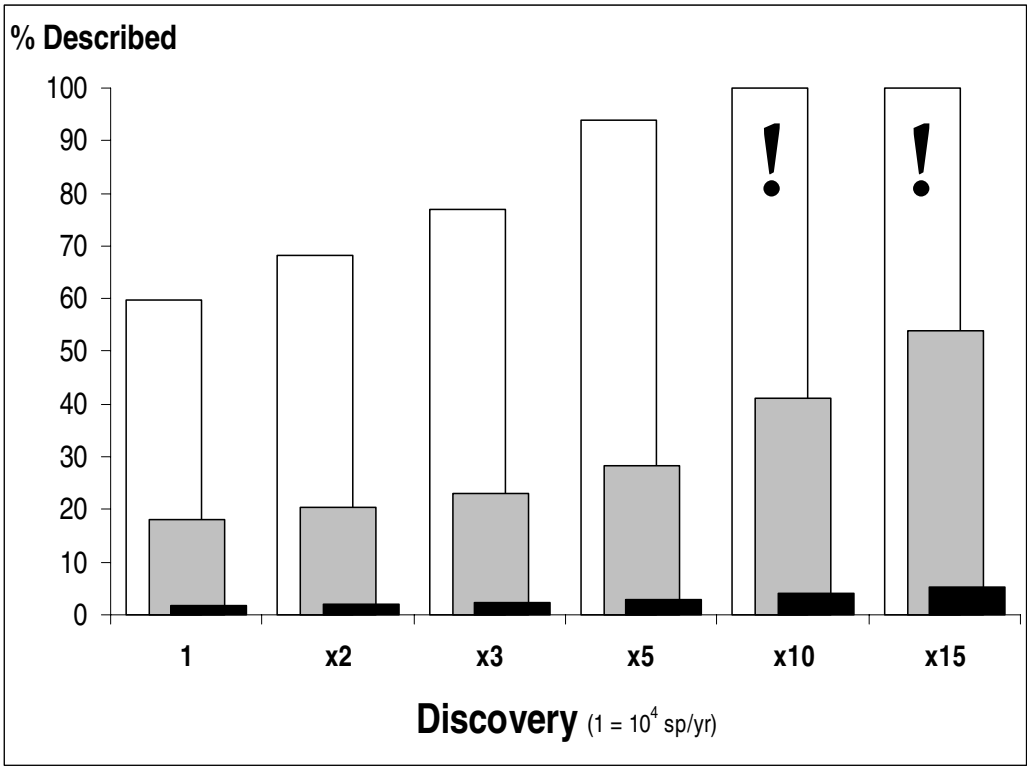

FIGURE 1. Total number of species described after 25 years, expressed as a percentage of the remaining total number of species (*y* axis), for different rates of discovery of new species (*x* axis; current values, 1 = 10,000 species/year). Three estimates of the total number of species living in year 2000 are considered: a very low estimate, 3 million (*white rectangles*), a middle estimate, 10 million (*grey rectangles*) and a high estimate, 100 million (*black rectangles*); in all cases, the number of species described up to year 2000 is estimated to be 1.5 million. Only if total biodiversity is very low and rates of discovery are 10 times current values (or higher), can the Encyclopedia of Life be totally accomplished in 25 years (% Described = 100; note the exclamation symbols, '**!**').

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Instead of answering this question now, I think it is more fruitful and relevant for conservation purposes to look at the problem from a different perspective. After all, why should we aim for 25 years to complete the Encyclopedia of Life? Why not any other figure, such as 10, 50, 100 or 250 years? In what follows, I will explore the relationships between the rate of description of new species, the time needed to complete the Encyclopedia of Life at that rate, and the fraction of species that are lost to extinction during this time span.

Whether we like it or not, every year while we invest money and resources in discovering and describing new species, at the same time a proportion of the total biodiversity is lost to extinction without ever being discovered, studied, or named, *i.e.*, the longer it takes us, the more species will go extinct. In other words, if, as Wilson (2003b) stated, every species on Earth fills the pages of the Encyclopedia of Life, then the faster we work, fewer species will get extinct, the more species will be classified, and the more pages will integrate the whole work. On the contrary, the slower the description of new species, the longer it will take us to finish the work, the more species will get vanished, and the shorter will be the final length of the Encyclopedia. Figuratively, it would not be a large, respectable Encyclopedia (*i.e.*, a book or set of books that cover a wide range of knowledge about a great number of species)… but a mere Brochure of Life: a small magazine dealing with some topics about a small number of species, but completely illustrated, and readily available on the Internet, of course!

For the sake of the argument, one could ask: how large do we want the Encyclopedia of Life to be? Or, in other words, how many unknown species can we 'afford' losing? For example, let's assume that, during the completion of the Encyclopedia, we can 'afford' losing a fraction (*%Loss*) of 10% of the total number of species found at the beginning of the survey (TS_0). Of course, we want to minimize the fraction of species lost to extinction during the completion of the Encyclopedia as much as possible; but, how much is feasible? I will discuss this topic later on. Now, let me please follow with the 10% example. In this way, if the total number of species at the beginning of the survey was 10 million (Figure 2, *dashed curves*), then the whole study would include only 90% of these species (9 million; TS_t), since 1 million species would have gone extinct during the survey (Figure 2, point *a*). Taking into account current, estimated values of speciation (*Spec*) and extinction (*Ext*), how long would it take for biodiversity to fall from 10 to 9 million? That is to say, how long would it take us to complete the whole inventory of life on Earth? If current extinction rates are 1,000 times the speciation rate, and if this is set to one species per 10^6 species per year, the answer (*t*) is estimated as slightly above 100 years (Figure 2, point *b*). In addition, if the number of known species at the beginning of the survey (Sk_{2000}) was 1.5 million, then 7.5 million species (9–1.5 = 7.5) correspond to unknown ones. Finally, if we have $t \sim 100$ years to describe all these new unknown species, then we should discover, describe and name them at a rate of $Nw \sim 71{,}000$ /year, or 7.1 times the current mean rate of description of new species (Figure 2, point *c*).

Obviously, this is only an example, and different values of *%Loss*, TS_0, Sk_{2000}, *Spec* and *Ext* might be considered (then, different values of *t* and *Nw* would be obtained). Specifically, values of *Spec* might be lowered to mimic expected declines in speciation rates due to various human activities (Rosenzweig 2001); on the other hand, values of *Ext* could also be lowered (for example, to 100**Spec*, in order to include other possible values, according to Pimm et al. 1995, Wilson 2003b, or May 2002) or alternatively increased (for example, to 10,000**Spec*, in order to track expected increases in extinction rates, according to Pimm et al. 1995). To keep things simple, I maintained *Spec* and *Ext* at the abovementioned rates to calculate *t* and *Nw* for each of the following scenarios (for simplicity, *Nw* was considered a constant through time): *%Loss* = 0.01, 0.1, 0.5, 1, 5, 10, 25 and 50%; TS_0 = 3, 10 and 100 million; and Sk_{2000} = 1.5. Results can be applied to better schedule the work needed to complete the Encyclopedia of Life. For example, in our model, if we estimate a certain value for the total number of species known at the beginning of the survey (in this case, Sk_{2000} = 1.5 million), we can first set a desired, constant rate of description of new species (Figure 2, *left axis*) and then calculate the time needed to complete the whole survey (Figure 2, *right axis*), knowing beforehand the number of species that will go extinct throughout the study (Figure 2, *horizontal axis*). Thus, if TS_0 is 3 million (Figure 2, *thin lines*) and new species are described 10 times faster than current rates, then it would take more than 10 years to complete the whole Encyclopedia, with more than 10^4 species becoming extinct (actually, some 30,000); however, if TS_0 is 100 million (Figure 2, *thick lines*), at the same rate of new species description, it would take close to 500 years to complete the whole Encyclopedia of Life and it would mean the loss of between 25 and 50 million species. On the other hand, one can first fix the time required to complete the Encyclopedia and then look for the rate of description of new species needed to achieve this end, always accepting that a certain number of species will go extinct during the survey. In this way, if TS_0 = 100 million and we want to complete the whole survey in 100 years, then some 10^7 species would be lost and the rate of description of new species should be very high, close to 100 times the current values (*i.e.*, 85 times); whereas, if TS_0 = 3 million, to

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complete the survey in 100 years, it would imply the net extinction of more than 10^5 species (actually, some 300,000), but it could be done at a slower rate of description of new species (close to 0.66 times the current rate).

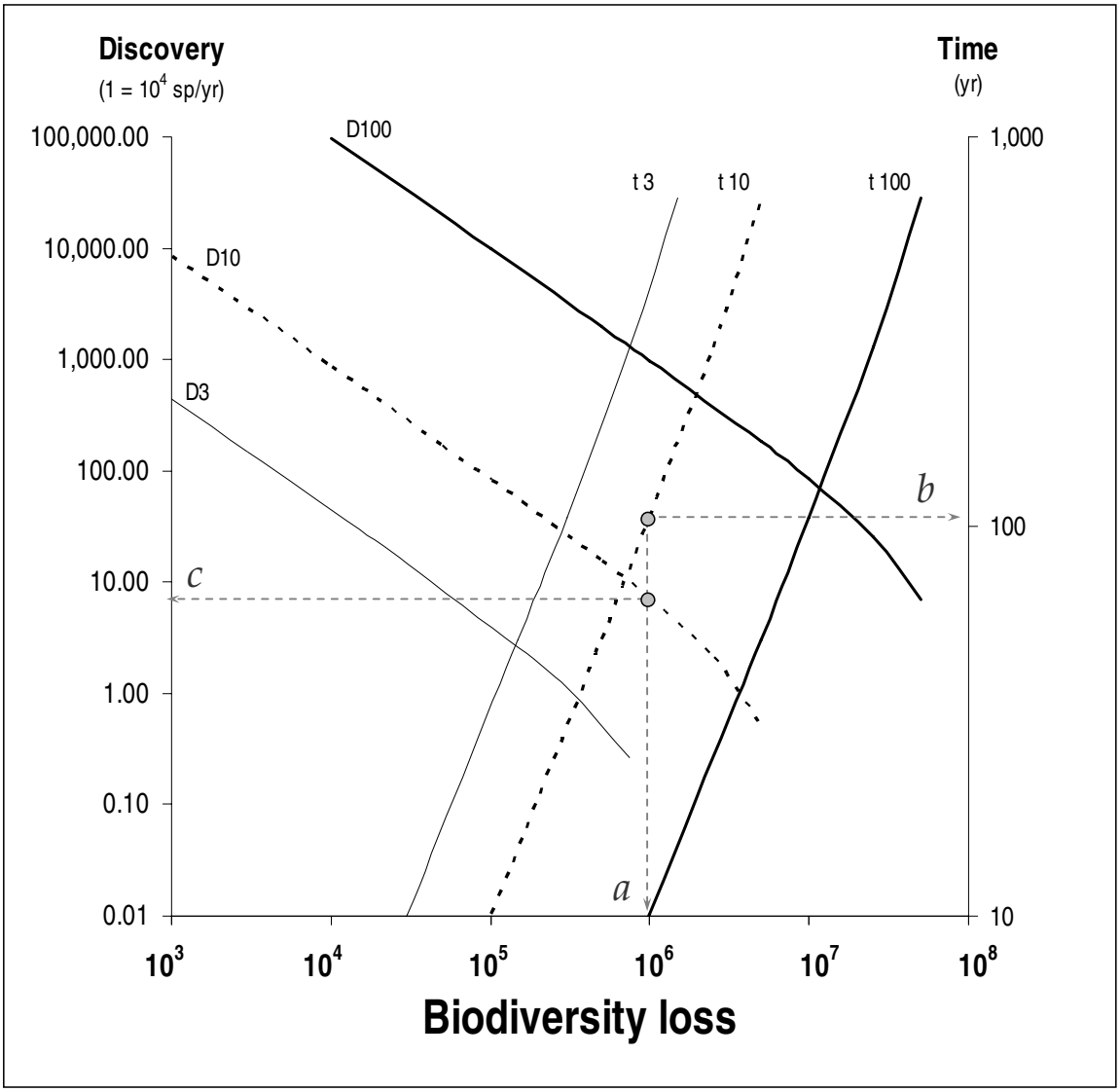

FIGURE 2. Relationships between the rate of description of new species ('Discovery', *left axis*; current values, 1 = 10,000 species/year; logarithmic scale), the time needed to describe all the species at that rate ('Time', *right axis*; in years; logarithmic scale), and the number of species that are lost to extinction during this time ('Biodiversity loss', *horizontal axis*; logarithmic scale). Three estimates of the total number of species living in year 2000 are considered: a very low estimate, 3 million (*thin curves*); a middle estimate, 10 million (*dotted curves*), and a high estimate, 100 million (*thick curves*). For each case, two curves are shown: discovery rates (*D* curves, like, D3 for 3 million species or D100 for 100 million) and time to complete the Encyclopedia of Life (*i.e.*, time to extinction of the species indicated in the horizontal axis; *t* curves, like t10 for 10 million).

Vertical and horizontal dotted lines are used in the figure as an example and evidence that, if the total number of species existing in year 2000 is estimated in 10 million (*dotted curves*), *ca.* 10^6 species (point ***a***) will be lost during the completion of the Encyclopedia (in a time span above 100 years, point ***b***) if we work at a rate of discovery close to 7 times the current one (point ***c***).

Concluding remarks: who will assemble the Encyclopedia of Life (if we are lucky) or the Brochure of Life (if we are not)?

As evidenced throughout this paper, and as noted previously by May (2004), it is unrealistic to think that the completion of the Linnaean enterprise (to use the name proposed by Wilson 2005) could take only one generation, unless the total number of species on Earth is much smaller than thought. In the same sense, Scotland et al. (2003) observed that the pace

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of progress towards the completion of the Encyclopedia is too slow, as indicated by some measures of the rate of taxonomic progress across several groups of organisms that show a 'glacial rate of advancement'. Thus, Wilson's (2004) estimate of the time needed to discover Earth´s entire biodiversity can be judged as over-optimistic. Discussing the relationships between taxonomy and conservation biology in the current Century of Extinctions, Dubois (2003) observed that, sometimes, in order to obtain funds and support, one must propose *positive* programs, based on *optimistic* appreciations, predictions or aims (Dubois' emphasis). However, such an attitude has little to do with a scientific evaluation of the problem. In this way, if Wilson's (2004) opinions are adopted by the scientific community, they could lead to the wrong conclusion that we do not need many changes to complete the inventory of living species on Earth before many of them go extinct. On the contrary, some authors have emphasized that increasing considerably the current efforts to collect and describe the vanishing species of our planet in the coming decades is extremely important, certainly much more urgent than many other apparently more fashionable vast scientific projects nowadays in progress (Scotland et al. 2003, Dubois 2008).

After analyzing some advances in the recent history of systematic biology, Scotland et al. (2003) stated that the main reason why the Encyclopedia is not yet completed is only because there are not quick answers (like the much publicized initiatives of DNA taxonomy and web publication) to the inventory shortfall: added technology does not necessarily increase taxonomic knowledge, as opposed to enhanced investment in taxonomic expertise (Scotland et al. 2003). In the same sense, Dubois (2008) concluded that taxonomy needs thousands of arms and brains much more urgently than personal computers, advanced techniques, or the Internet. But, how many thousands of new arms and brains are we talking about? Indeed, following the line of reasoning developed along this paper, *it is possible* to roughly estimate the number of practising taxonomists needed to complete the Encyclopedia in a given time span and at a known rate of description of new species. If the existing 6,000–7,000 taxonomists (Schnack & López 2003, Wilson 2004) are responsible for the current rate of description of new species (estimated in 10,000/yr; but see Stork 1997 for a higher estimate of 15,000/yr, very close to the recent value of 16,969 new species described in 2006, according to the First Annual State of Observed Species Report; Anonymous 2008), then the mean rate of description of new species per taxonomist is located somewhere between 1.4 and 2.5. But these figures may be over-optimistic as well. Evenhuis (2007) revised the taxonomic productivity of the Fiji Terrestrial Arthropod Survey, supported by the National Science Foundation, and concluded that, essentially, the mean taxonomic productivity was much lower than one new species described per ten years per person! For the sake of the argument, and taking into account some of the reasons exposed above (like the proposed help provided by technical assistants and novel technologies), I admit that the mean taxonomic productivity could be enhanced maybe up to 5 new species per year per taxonomist. Then, following with the example previously considered (*i.e.*, an estimated total number of 10 million species; 1.5 million species already known at the beginning of the survey; *%Loss* = 10%, $t \sim$ 100 years, $Nw \sim$ 71,000/year), a small 'taxonomic division' of some 14,000 taxonomists (more or less, twice the current number of practising taxonomists) would be needed, all of them working at the same high, 'elite' average rate of *5 new species per year per taxonomist!* (Figure 3*a*); or, alternatively, a larger 'division' of some 28,500 taxonomists describing 2.5 new species per year per taxonomist (results not shown); or, finally, a whole 'taxonomic army' of some… *51,000 taxonomists!* (*i.e.*, some 7.5 times the actual numbers; Figure 3*b*), all of them working at a lower, more 'relaxed' rate of description of 1.4 new species per year (*i.e.*, the lowest current value). Now, I will answer the question left unresolved previously: as abovementioned, should the total magnitude of biodiversity be close to 10 million species, the completion of the Encyclopedia would take much longer than the 25 years proposed by Wilson (2004), unless *Nw* is multiplied by a factor much higher than 15. But, in this case, how many taxonomists are necessary to complete the Linnaean enterprise? If the mean rate of description of new species is 5 per year per person (indeed, an optimist situation, but optimistically not impossible to achieve), then some 66,000 taxonomists are required; if the mean rate of description is 2.5 (the highest current value), some 132,000; and if it is only 1.4 (the lowest current value), some 236,000 taxonomists are desperately needed, right now, and every year during the following 25 years! Dubois (2008) was right when he talked about thousands of arms and brains… The obvious question is: *where are these magic numbers of practising and qualified taxonomists that spend their professional lives describing new species?* But I am sure you already know the answer, of course: *nowhere!* That is the taxonomic impediment!

Surely, much more money and manpower should be directed towards research programs involved in species collection, inventory and description, in this way promoting a strong acceleration of taxonomic activities (Dubois 2003). Regrettably, even if funds were miraculously made available for this purpose, implementation of such research programs in this day and age would be impossible, as it would first require taxonomic practice to overcome the current taxonomic impediment. A greater allocation of resources for collections and basic research, but also for the establishment of permanent positions for taxonomists, are examples of cost-effective initiatives that have been successfully implemented to address the low speed with which new species are described (de Carvalho et al. 2007). The international scientific com-

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munity must invest considerable energy in obtaining support from society and raise funds to train and hire thousands of competent practising taxonomists in order to collect and describe the millions of species that, otherwise, will become extinct in a few decades without receiving a name (Dubois 2008). Or else, the Encyclopedia of Life could become only a simple but colourful Brochure of Life, and conservation priorities would continue being restricted to what little we know about only a small fraction of the total biodiversity.

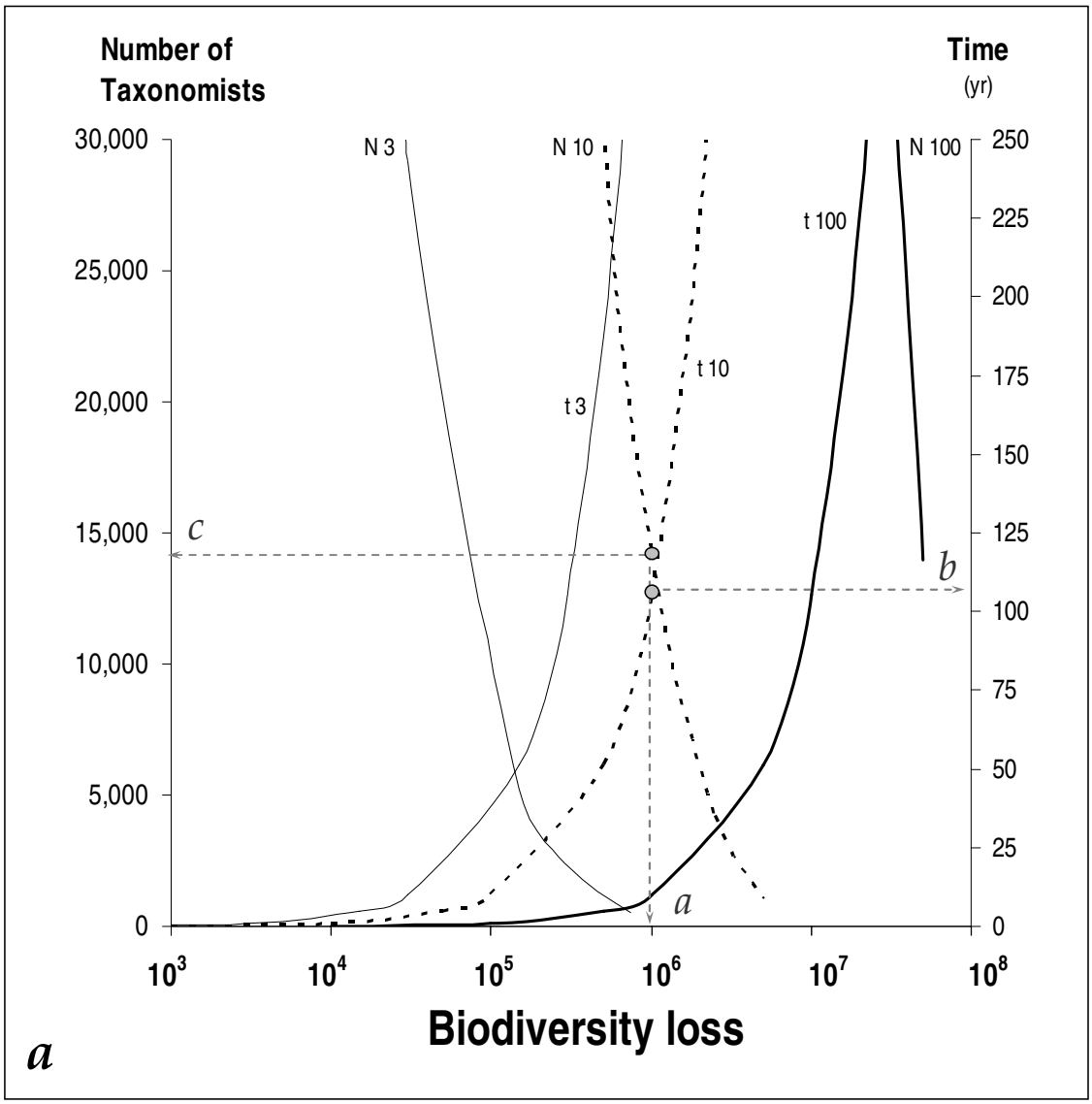

FIGURE 3. Relationships between the number of taxonomists needed to complete the Encyclopedia of Life ('Number of taxonomists', *left axis*; arithmetic scale), the time needed to describe all the species by that number of experts ('Time', *right axis*; in years; arithmetic scale; for simplicity, limited to 250 years), and the number of species that are lost to extinction during this time ('Biodiversity loss', *horizontal axis*; logarithmic scale). Three estimates of the total number of species living in year 2000 are considered: a very low number of species, 3 million (*thin curves*); a middle one, 10 million (*dotted curves*), and a high estimate, 100 million (*thick curves*). For each case, two curves are shown: numbers of taxonomists (*N* curves, like, N3 for 3 million species or N100 for 100 million) and time to complete the Encyclopedia of Life (*i.e.*, time to extinction of the species indicated in the horizontal axis; *t* curves, like t10 for 10 million). (*a*) If mean, individual rate of description is set to 5 new species per year per taxonomist; and (*b*) if mean, individual rate of description is set to 1.4 new species per year per taxonomists (current value).

In (*a*), vertical and horizontal dotted lines are used in the figure as an example and evidence that, if the total number of species existing in year 2000 is estimated in 10 million (*dotted curves*), *ca.* 10^6 species (point ***a***) will be lost during the completion of the Encyclopedia (in a time span above 100 years, point ***b***) if some 14,000 taxonomists are constantly describing new species at a high, optimistic rate of 5 species per year per taxonomist.

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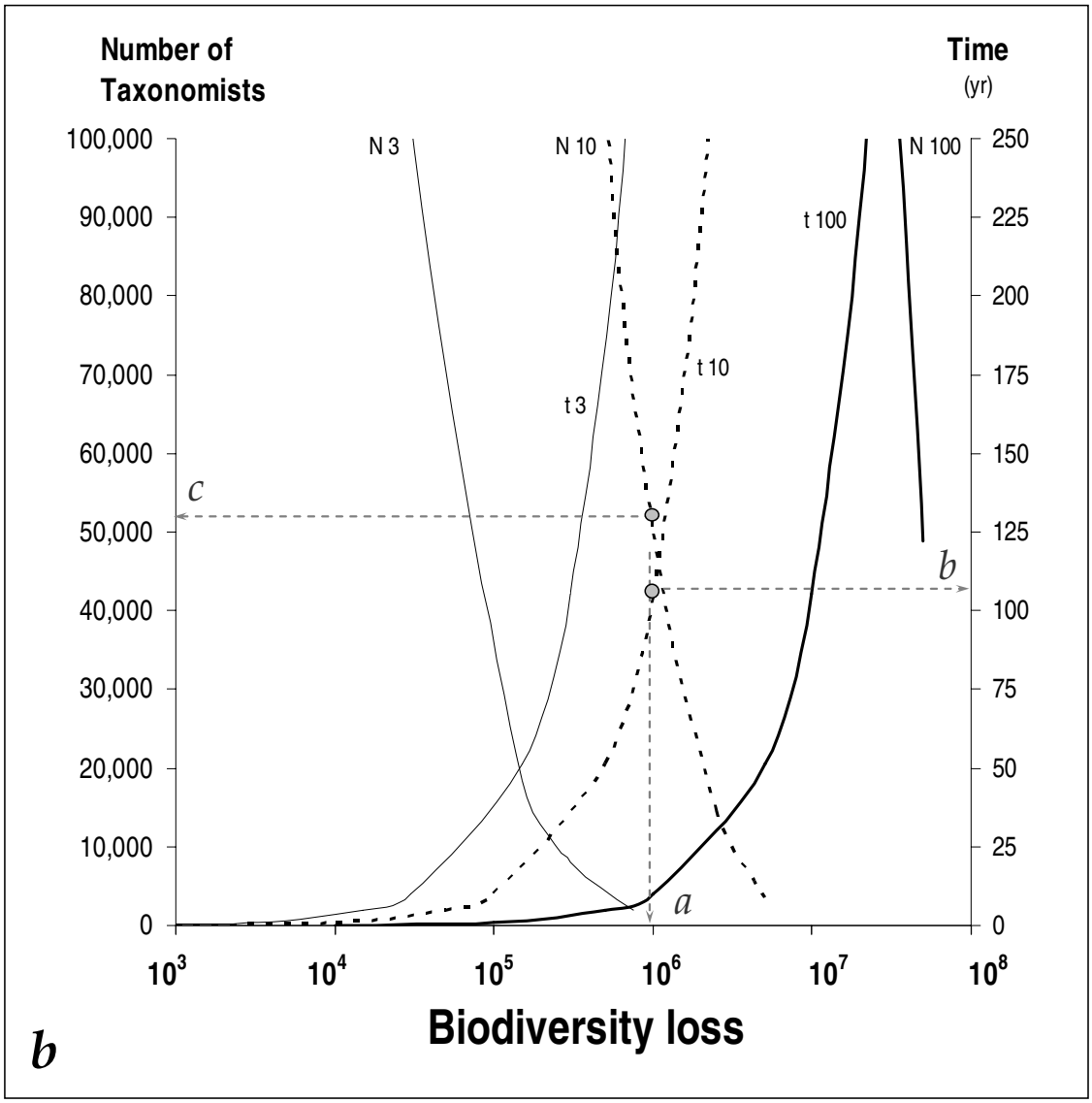
In (*b*), the same number of species (point ***a***) will get extinct during the completion of the Encyclopedia (during the same time, point ***b***) if some 51,000 taxonomists are constantly describing new species at the current, low rate of 1.4 species per year per taxonomist.



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